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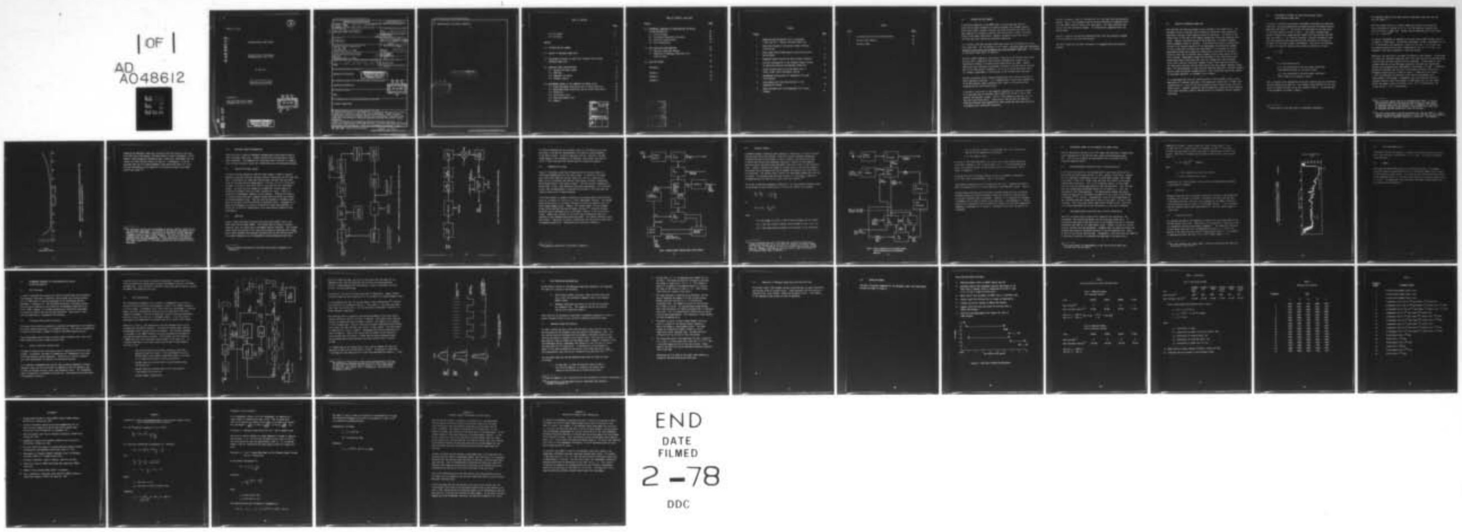

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AMBIGUOUS RANGE STUDY REPORT

Federal Electric Corporation
Vandenberg AFB, Calif. 93437

30 June 1977

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Prepared for

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Low Noise Range Data

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A continuing objective at the SAMTEC West is to provide data which will permit evaluation of inertial guidance (IG) system performance. Recent computer simulations indicate that better results could be obtained if low noise range data were used instead of range and range data obtained from current instrumentation.
Several techniques are presented for obtaining low noise range data. It is shown that comparatively simple modifications to existing instrumentation systems may prove to be satisfactory. Tests are recommended to determine if these

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20. modifications are actually feasible.

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1.0 INTRODUCTION AND SUMMARY

A continuing objective at the SAMTEC West is to provide data that will permit the accurate evaluation of inertial guidance (IG) systems launches. Historically range, azimuth, elevation and range rate data from radars have been combined in a regression analysis with the IG data in order to estimate certain error model coefficients. However, systematic errors and noise in the radar data have limited the achievable accuracies.

It is possible that more accurate coefficient values can be obtained using low noise range data. For the purposes of this report, low noise range data containing systematic errors which can be modeled are called ambiguous range data. This concept is explained in more detail in Section 2.

The basic premise adopted in this study is that for a sufficiently high signal-to-noise ratio, range noise from existing instrumentation systems can be significantly reduced if suitable system modifications are made. Computer simulations were conducted as described in Section 3, and the results indicate that if the range noise is reduced to .01 ft. at a 160 sps data rate, there is a dramatic improvement in the accuracy of the IG coefficient estimates.

Section 4 discusses several system configurations which could be employed to obtain ambiguous range data. It is suggested that a stand-alone augmentation of the WTR coherent signal processing (CSP) radars is the most practical configuration for verification tests.

In Section 5, the errors in the suggested augmented CSP system are analyzed. It is concluded that on Minuteman type flights from liftoff + 125 to +500 seconds, the dominant systematic errors in the ambiguous range data will be bias and scale factor errors. These results indicate that the ambiguous range data obtained from augmented CSP radar systems may have great potential in guidance error coefficient evaluation.

Section 6 proposes a specific configuration for a CSP radar test and evaluation program. Most of the equipment required could be obtained on a temporary basis from the SAMTEC inventory and/or on a lease basis. This would minimize costs for the test and evaluation program. The configuration suggested favors the MPS-36 radar.

Section 7 explains how the data obtained during a test and evaluation program could be gathered, processed and analyzed.

Section 8 summarizes the major milestones in a suggested test and evaluation program.

2.0 CONCEPT OF AMBIGUOUS RANGE DATA

Data obtained from tracking systems contain systematic and random errors. The systematic errors in the data can be reduced by calibration, data processing algorithms, and post flight regression analysis techniques. The effect of the random errors in the data can be reduced through data processing smoothing techniques. However, such data correction techniques may, in certain instances, induce systematic trends in the data. In any event the accuracy is essentially limited to the inherent precision of the measurement and calibration systems. In order to meet more stringent user requirements it is necessary to utilize measurement systems which reduce the random errors (precision) to the lowest practical level and to eliminate those systematic errors which cannot be accurately modeled. Measurement systems are described in this report which could conceivably produce range data with "very low" random errors and systematic errors which could be "accurately" modeled in post flight regresssion analysis. The range data resulting from such modifications has been termed "ambiguous range" data. The term ambiguous is used since the resulting range data, although extremely precise, needs an external standard such as a post flight data regression program to accurately determine its systematic error content.

It is postulated that practical modifications of existing SAMTEC systems can be made which will produce range data at 100 samples per second (sps) or higher with random errors of .1 foot or less and systematic errors limited to bias and scale factor errors. Computer simulations made on range data containing these characteristics have indicated a greatly improved ability to accomplish inertial guidance evaluation.

3.0 PRELIMINARY ESTIMATES OF COEFFICIENT RECOVERY RATIOS USING AMBIGUOUS RANGE DATA

In order to illustrate the potential improvement achievable with ambiguous range data, covariance comparisons were made using the Performance Analysis Department IGR filter.(1) The initial IGR covariance run was made using six mainland radars as listed in Table 1. Four radars provided range, azimuth, elevation and range rate data (RAER) while two provided only RAE data (see Table 1). For simulation purposes, a nominal Minutemann trajectory was assumed and data uncertainties were used which are believed to be typical of the radar systems' performances. The results are presented in Table 2 in terms of recovery ratios which are defined as follows:

$$R_i = \frac{\sigma_o}{\sigma_i}$$

where

- R_i is the recovery ratio
- σ_i is the uncertainty of the error model coefficient value before the data run, (a priori value).
- σ_o is the uncertainty of the error model coefficient after a data run, (a posterori value).

Thus, a recovery ratio approaching unity would indicate that the uncertainty was not reduced by the data run. The recovery ratios obtained for the runs using six radars are shown in the last column of Table 2. The designations of the parameters are given in Table 3.

---

(1) A description of the IGR filter is contained in Reference 1.

The subsequent IGR runs were made using only ambiguous range data from the four CSP radars.[(2)]

The first column (case 1a) of Table 2 shows the recovery ratios when the noise uncertainty is reduced to .01 ft. with the same data coverage intervals as for the six radar case. Another run was conducted with a noise level of .1 ft. (case 1b)[(3)]

The overall improvement as compared to the multi-station RAER solution (case 3) is dramatic in both cases. The smallest improvement is seen in parameters 16, 19, 21, 26 and 28 which are reduced by a factor of 2 for the .1 ft. σR case, but are reduced by more than an order of magnitude for the .01 ft. σR case. Improvement in the other parameters is even more dramatic.

Additional runs were made to estimate the effects of data dropouts. As described in Section 5.3, ambiguous range data from a CSP radar can only be provided during intervals when the radar achieves fineline phaselock. Investigation of data coverage intervals on past Minuteman operations indicates that intermittent unlocks can be expected until approximately +128 seconds in flight. In addition, Reference 8 indicates that the error in the range refraction correction on Minuteman launches may be as shown in Figure 1. Refering to this figure, it will be noted that the refraction error could be detrimental until approximately T+120 seconds. Consequently runs were conducted using data coverage intervals from T+128 seconds to T+500 seconds for all four radars. Results are shown in case 2a of Table 2 for a .01 ft. σR uncertainty, and in case 2b for a .1 ft. σR uncertainty.

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(2) One of the four radars used was at Vandenberg AFB (VAFB). In actual practice data from this site would be noisy because of flame effects. As improved results could be obtained with an augmented CSP system at an alternate location it was decided to use the VAFB site rather than to reprogram the IGR software for a new site location.

(3) The noise levels used in the IGR simulation were .025 and .0025 ft. This is because the simulation program operates at 10 sps and data can be provided at 160 sps. Noise is therefore reduced by a factor of 4. See Appendix 1.

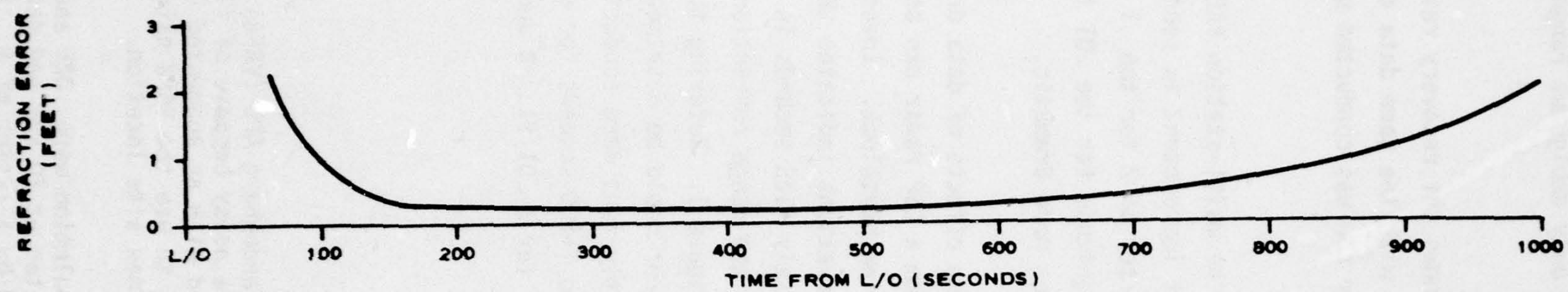

FIGURE 1 UNMODELED RANGE REFRACTION ERROR VS MINUTEMAN FLIGHT TIME FOR A "TYPICAL" MAINLAND RADAR SITE.

Comparing the ambiguous range runs using data from T+35 seconds to the runs using data from T+128 seconds, the major effect is seen in parameters 1 and 8. However, these parameters nonetheless show a significant improvement over the current six radar solution (case 3 of Table 2). Consequently, it can be concluded that use of suitable ambiguous range data would result in a significant improvement in the capability to accurately estimate error model coefficient values.(4)

(4) The covariance results can be considered as giving a relative indication of the achievable improvement. An estimate of the absolute improvement can be obtained in a state vector simulation using data which includes unmodeled systematic errors as well as data dropouts. This type of simulation was attempted using the "ARMS" program. However, results were unacceptable because of the software mechanization. Such simulations can be made with the "TRAM" program which is now being developed by the Performance Analysis Department.

4.0 AMBIGUOUS RANGE CONFIGURATIONS

There are several practical equipment configurations which could be used to obtain ambiguous range data. Several possibilities are described in subsequent paragraphs. The augmented CSP system described in Section 4.3 appears to be the most practical choice for a preliminary test and evaluation program.

4.1 Improved CSP Radar System

A simplified block diagram of a WTR CSP radar system is shown in Figure 2. Ambiguous range data could be obtained by merely integrating the CSP range rate data. Investigation of range rate tracking data indicates that the noise level of such data would be approximately .1 ft./sec. (1σ) at a 10 sps rate. As shown in Section 3, this noise level is too large for the anticipated useage. The noise could be reduced by introducing a counter capable of resolving the Doppler count to a small fraction of a cycle. There is a significant disadvantage, however, to this approach. Refering to Figure 2, it should be noted that such a Doppler counter would be within the system's very narrow phaselock loop. The loop could be expected to introduce systematic errors which could be difficult to accurately model. Consequently, it would be advantageous to utilize a system with a wider loop bandwidth, or better yet to utilize a system which is not constrained by phaselock loop performanace.

4.2 WSMR DVES

Figure 3 shows the Doppler Velocity Extraction System (DVES) used at the White Sands Missile Range (WSMR). This system does not employ a standard phaselock loop, but rather uses a narrowband receiver technique. The recieved pulses cause the receiver IF to "ring" and to output a continuous wave signal with a phase response which matches the phase shift on the received pulses.[5] This phase information can be integrated to provide ambiguous range data.

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[5] A more detailed explanation of the DVES can be found in Appendix 2 of Reference 2.

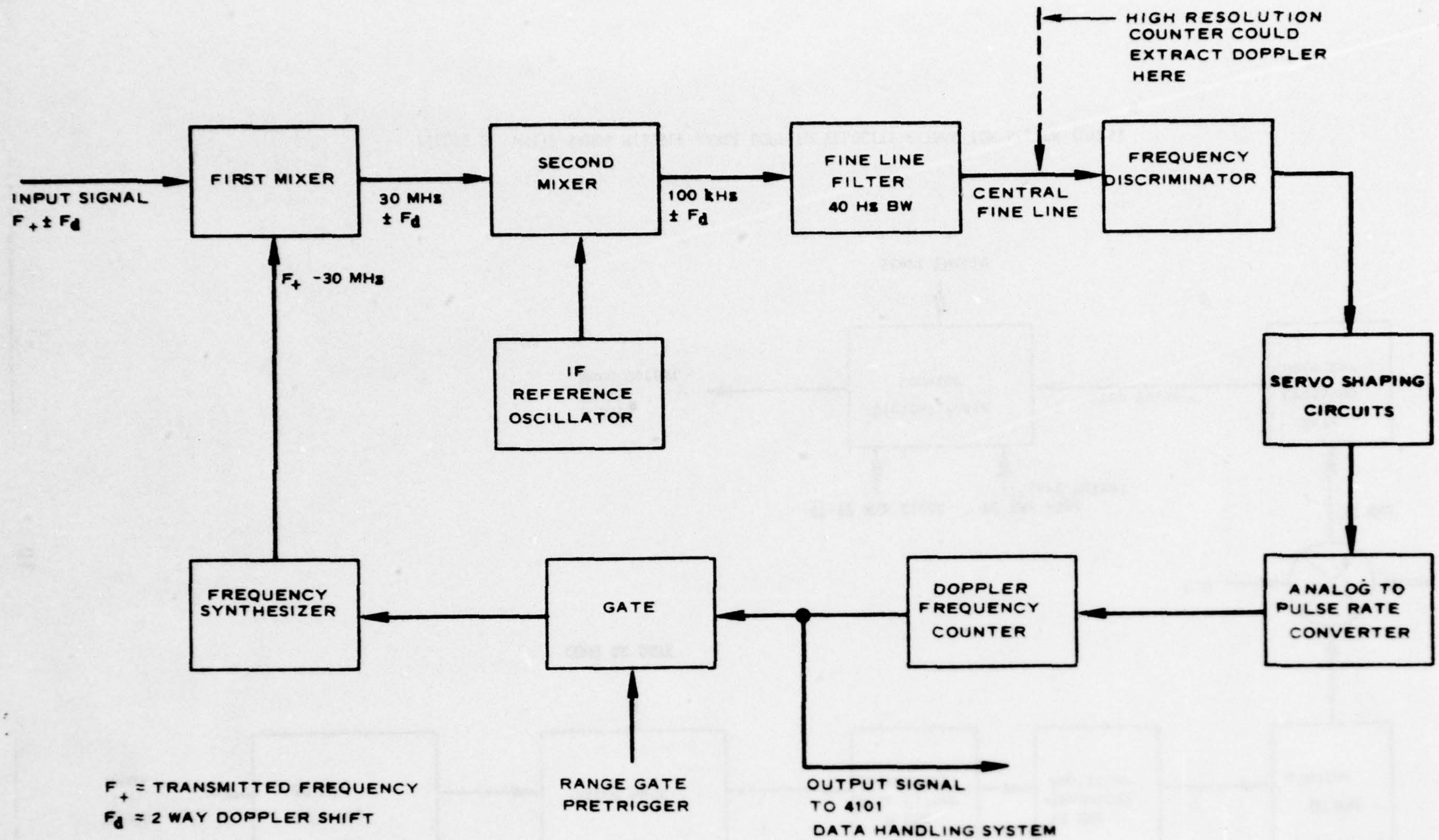

FIGURE 2 SIMPLIFIED DIAGRAM OF THE COHERENT SIGNAL PROCESSOR TRACKING LOOP

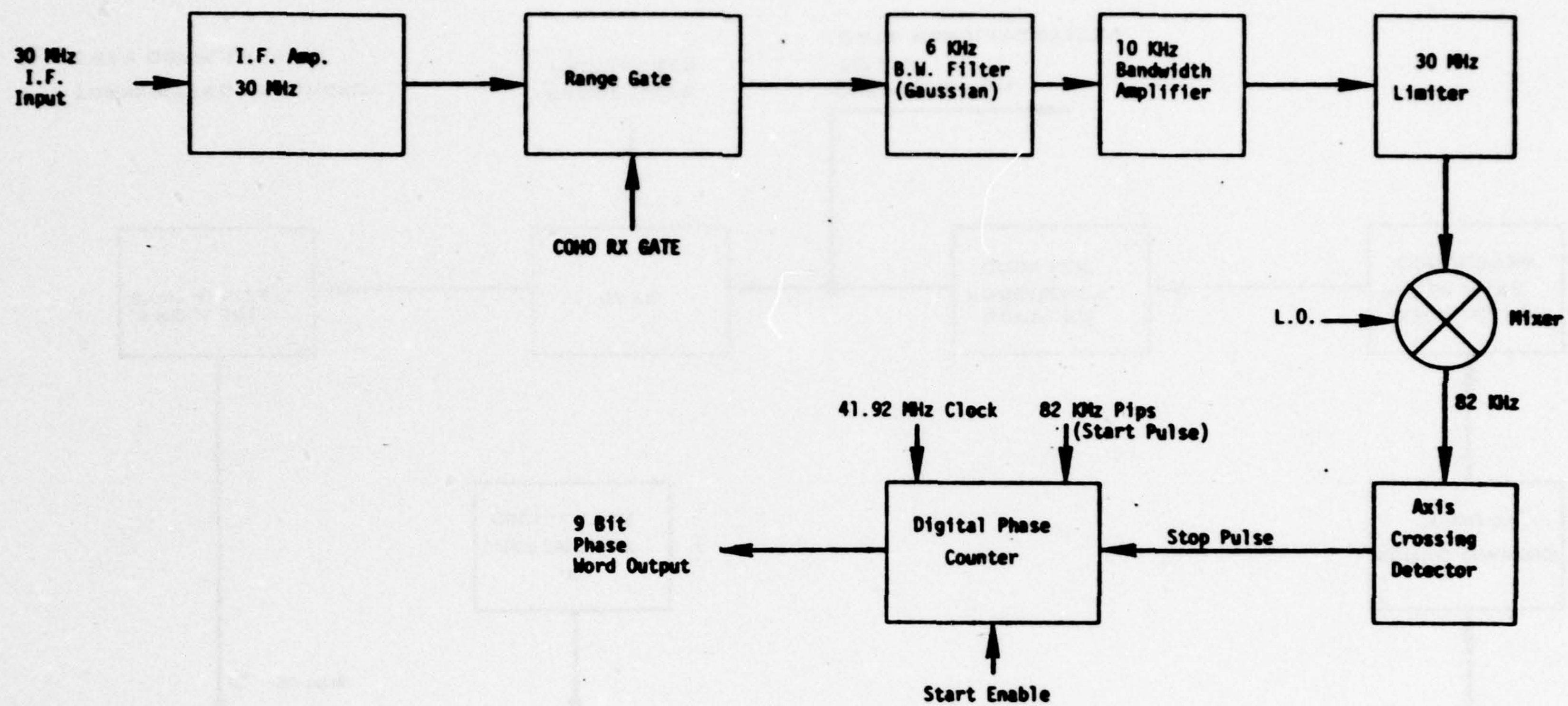

FIGURE 3 WHITE SANDS MISSILE RANGE DOPPLER VELOCITY EXTRACTION SYSTEM (DVES)

It could be expected that the systematic errors in the DVES would be lower than those in the WTR CSP system because the effective system bandwidth of the DVES is wider. (6 kHz as compared to 40 Hz) Certainly, the DVES system appears to hold promise as an ambiguous range system, and could be useful in obtaining satellite tracking data for evaluation purposes.

4.3 Augmented CSP System

Figure 4 illustrates a possible configuration which could be added as a stand-alone augmentation to a CSP radar system. In operation, the range gate signal would open the receiver input just prior to a return pulse. When a pulse is received, the receiver video output activates a monostable multivibrator which in turn arms a counter. The multivibrator automatically resets after .5 usec., and terminates the counter measurement. This technique ensures that the measurement is made during a portion of the pulse when the signal-to-noise ratio is nearly maximum.

The HP 5370 counter is capable of measuring the average phase of each received pulse to a fraction of a cycle in a .5 usec. measurement interval. The average phase of each pulse is, of course, ambiguous as there are numerous cycles of phase change between pulses. However, the integer number of cycles between pulses can be resolved from the CSP range rate data.[6] Therefore the augmentation can be considered to be a fine phase "vernier" of the existing CSP system. However the "vernier" is not within the CSP phaselock loop and is therefore a very wideband phase measuring system. This feature minimizes systematic errors. There are, of course, system errors not the least of which could be wideband system noise. These errors are discussed in Section 5.

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[6] The ambiguity resolution is described in Appendix 3.

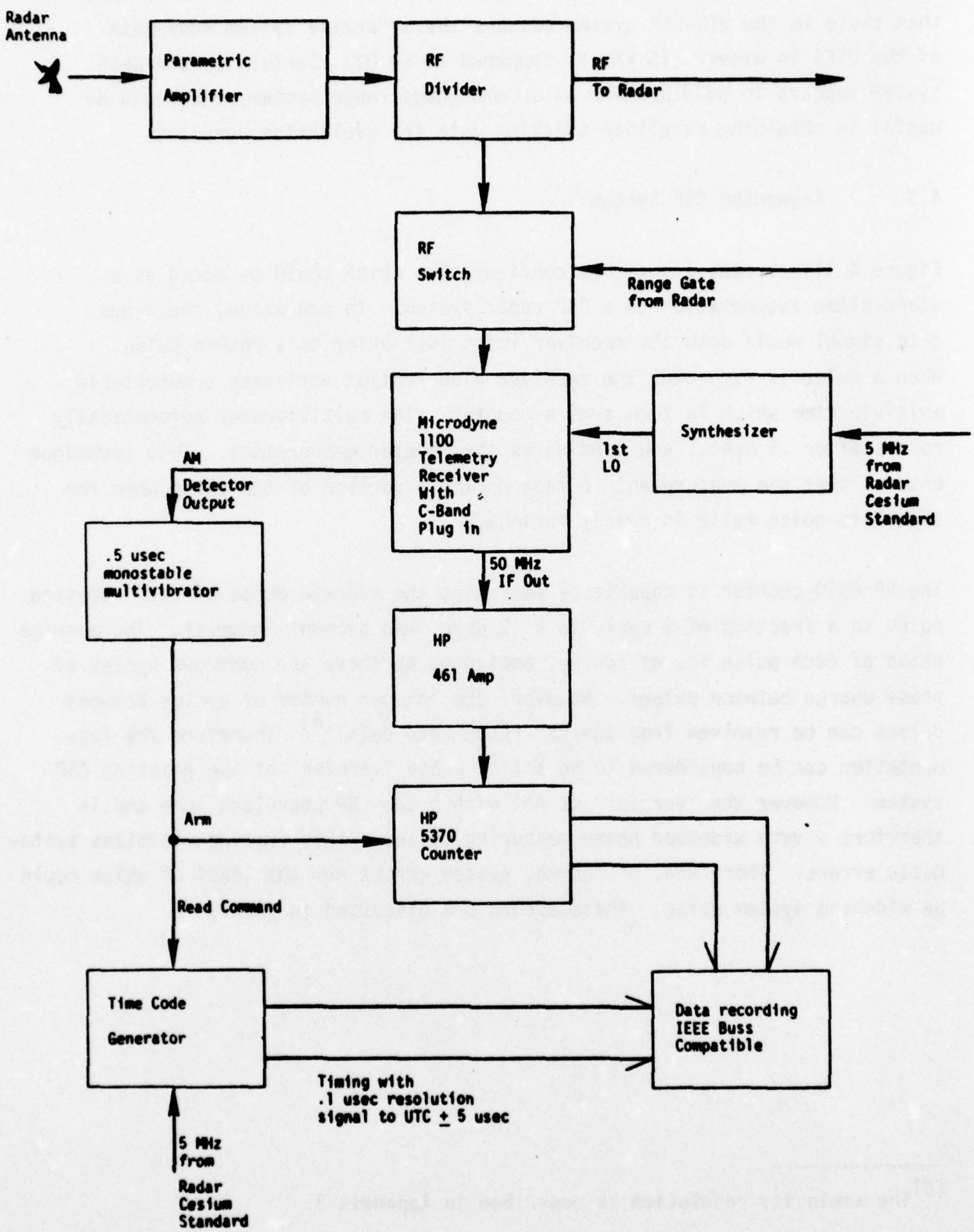

FIGURE 4 AUGMENTED COHERENT PROCESSING RADAR SYSTEMS (PROPOSED)

4.4 Telemetry Doppler

A telemetry Doppler system has been suggested in references 3, 4 and 5 to obtain velocity data from a non-coherent, relatively unstable telemetry transmitter. A modified version of this system is shown in Figure 5 and could be utilized to obtain both velocity and ambiguous range data. Markers in the telemetry data are used to synchronize the measurement intervals at each of four receiving sites. Counter 1 measures the number of integer cycles of the carrier between the markers and also measures the period between the markers with a precision of 10 picoseconds. The second counter repeats this measurement between the next set of markers. By recording data from both counters it is possible to obtain an incrementing count of both carrier cycles and clock interval.[7]

The system of equations suggested in Reference 3 for the telemetry Doppler system can be written in the following form if relativistic effects are excluded:

$$\frac{N}{\Delta T_i} = \frac{N}{\Delta T_t} \cdot \frac{1}{1 + \frac{1}{C}\frac{\Delta R_i}{\Delta T_i}}$$

or

$$\Delta R_i = C\Delta T_i \cdot \frac{\Delta T_i - \Delta T_t}{\Delta T_t}$$

where

- N is the number of cycles of the RF carrier between carrier markers
- ΔT_i is the time interval between carrier markers at the "ith" site
- ΔT_t is the time interval between carrier markers at the transmitter

---

[7] It may be expected that this "flip-flopping" of counter readings would introduce an occasional cycle slip when, for example, one counter somehow fails to start on the same RF carrier zero crossing that the other counter stops on. However, this type of cycle slip error is easily corrected in the hardware scheme shown in Appendix 2.

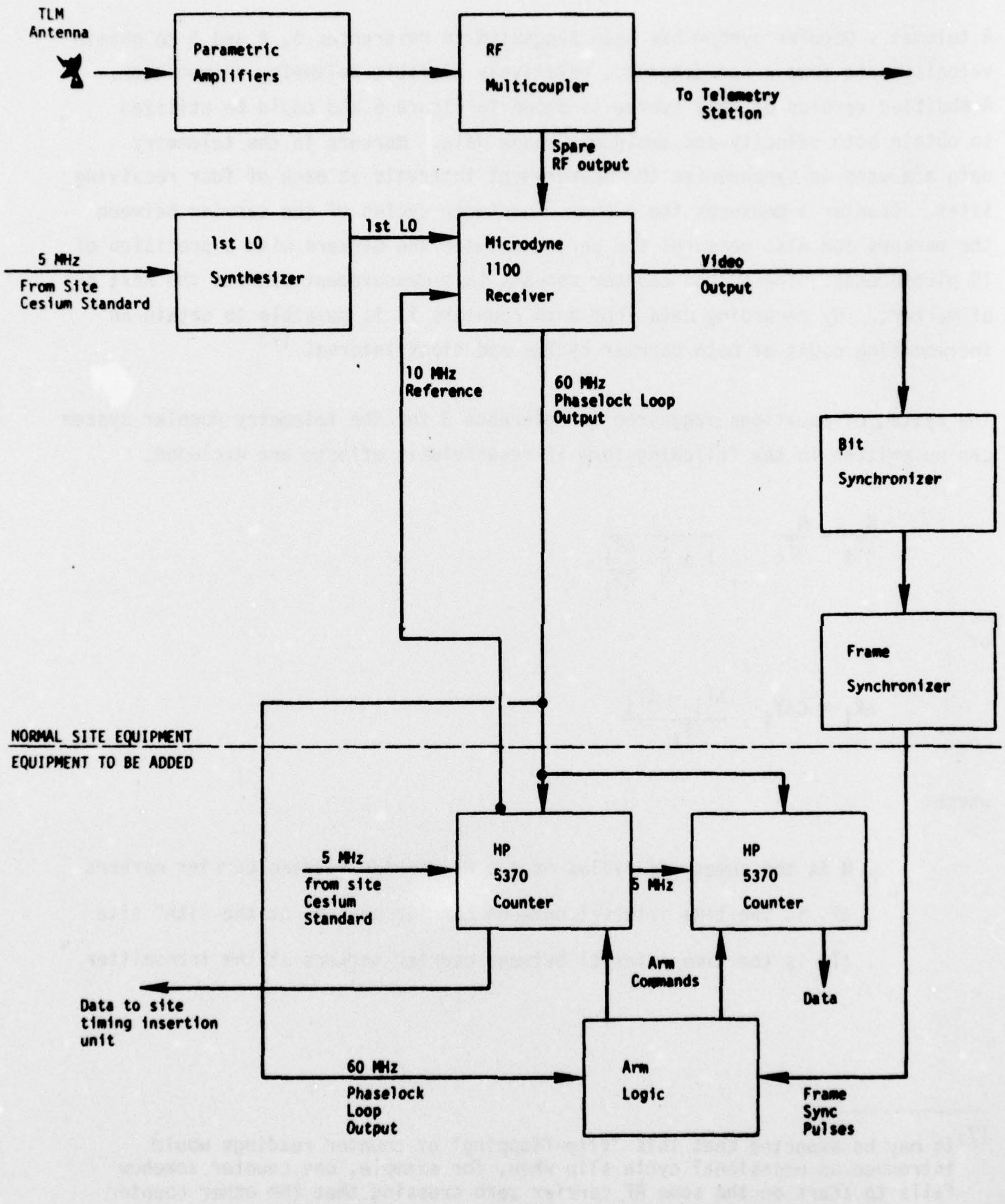

FIGURE 5 POSSIBLE CONFIGURATION OF THE TELEMETRY DOPPLER SYSTEM FOR MEASURING VELOCITY AND AMBIGUOUS RANGE DATA

. ΔR_i is the radial change in range between the "ith" receiving site and the vehicle between carrier markers

. C is the speed of light

The error in the range measurement (ΔR_i) due to the counter timing resolution is derived in Appendix 1 and is approximately .01 ft. As the Minuteman marker rate is 33 times per second, the equivalent error at 10 sps would be .006 ft. (Refer to Appendix 1.)

The phase noise of the telemetry Doppler system is estimated in Reference 6 to be .005 cycles or approximately .0025 ft. at S-band.

There would be systematic errors introduced by the 5 kHz. Phaselock loop which might be expected to be of a similar magnitude to the WSMR DVES system. (See 4.2)

These estimates indicate that the telemetry Doppler system would be a potential candidate system for obtaining ambiguous range, particularly on vehicles which do not carry coherent radar transponders. However, it is necessary to instrument a redundant site in order to obtain useful test data. (See Reference 3.) Consequently, for a preliminary test and evaluation program, the CSP radar augmentation suggested in paragraph 4.3 is simpler to implement as only one site need be instrumented.

5.0 MEASUREMENT ERRORS IN THE AUGMENTED CSP RADAR SYSTEM

Material developed on Section 4.3 of this report indicated that a comparatively simple augmentation of the WTR CSP radars would provide ambiguous range data. This section discusses the measurement errors associated with the suggested augmented system.

5.1 Range Measurement Uncertainty Due to Timing Resolution

As discussed in Section 4.3, the average phase of each return pulse will be measured by the 5370 counter during a .5 usec. segment of each pulse. Because of pulse amplitude fluctuations, as well as pulse shape changes, the trigger (see Figure 7) level will "jitter" back and forth with respect to the actual leading edge of the pulse. This is not a problem, however, as the trigger pulse will arm the counter <u>and</u> strobe the time code generator. Thus, the time that the average phase measurement begins will be known to $\pm$ .1 usec, the resolution of the timing generator. The maximum delay between the timing reading and the start of the phase measurement will be 1 cycle of the 50 MHz. IF frequency,[8] or .02 usec. Consequently, a plot of the average phase of the received pulses can be made with an error of less than $\pm$ .12 usec in the time base. For a worse case radial range rate of 20,000 ft./sec., the error in the phase measurement due to the timing error is less than $\pm$ 8 degrees.

5.2 Range Measurement Uncertainty Due to Carrier Phase Noise

There will be phase noise on the carrier induced by the transmitter, the transponder, the transmission medium, and the receiving system noise. To estimate the magnitude of the phase noise in the wideband receiver IF, spectrum photographs were made of the radar beacon return. However, no specific results could be inferred from the photographs. Attempts were also made to estimate the wideband phase noise by analyzing the noise in the CSP phaselock loop. Again, no specific conclusions could be made. Consequently, field tests must be conducted as described in Section 6 to determine the magnitude of the phase noise.

---

[8] The counter begins its measurements on the first positive going zero crossing after the arm pulse.

augmented CSP system. Figure 6 shows the signal-to-noise ratio in the 1.25 MHz final IF of the CSP radars on Minuteman launches.[9] It should be noted that the signal-to-noise ratio drops to approximately 20 dB at +500 seconds. Reference 7 indicates that the phase deviation due to the receiver noise is:

$$\phi n \simeq 57.3 \left(\frac{1}{2\rho}\right)^{1/2} \quad \text{degrees}$$

where

ϕ_n is the standard phase deviation, degrees

ρ is the IF signal-to-noise ratio.

Consequently, for a 20 dB signal-to-noise ratio the standard phase deviation is approximately 4 degrees.

5.3 Refraction

Ambiguous range data will be adversely affected by refraction, and appropriate corrections must be made to the data. Reference 8 indicates that the error in the range refraction correction, as implemented at the SAMTEC, should be within the bounds shown in Figure 1 for Minuteman launches. It will be noted that for elevation angles above approximately 5°, the error should appear as a small bias.

5.4 Scale Factor Error

The raw data provided by the augmented CSP system will be average phase of the received pulses versus time. These data will be converted to range versus time by a conversion routine as described in Appendix 1. The conversion introduces a scale factor error which will be approximately equal to (1×10^{-8}) R ft., where R is the range from the vehicle to the receiving site, ft. For example, at 2000 nautical miles the error is (1×10^{-8}) (2000) (6000) $\simeq$ .1 ft.

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[9]The plots represent the signal power in the pulse divided by the receiving system noise in the final IF.

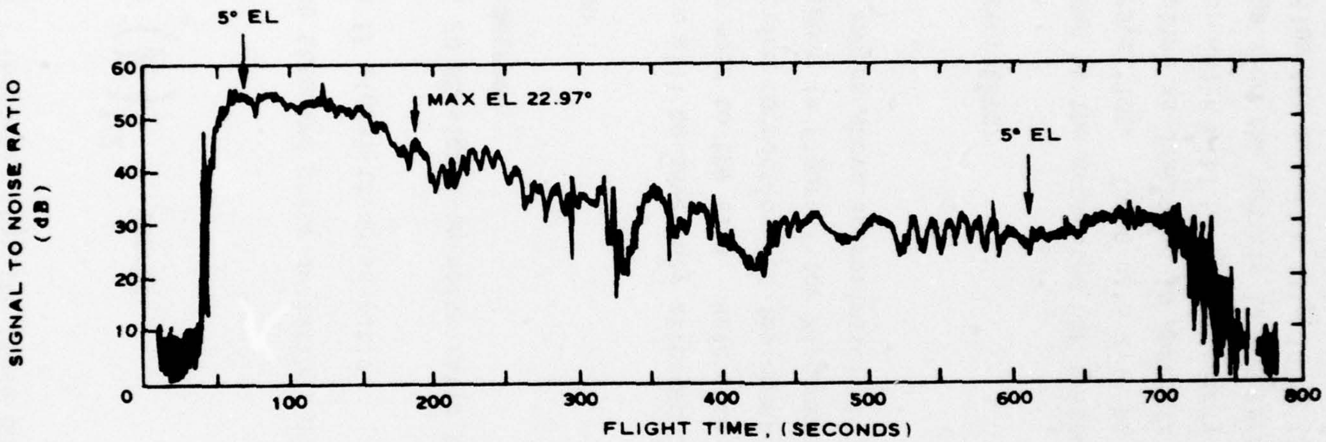

FIGURE 6 SIGNAL – TO – NOISE RATIO IN THE RADAR FINAL IF VERSUS FLIGHT TIME ON MINUTEMAN LAUNCHES.

5.5 Phase Measurement Error

The Hewlett Packard 5370 computer can measure the average phase of each return pulse to an accuracy of approximately 1° in .5 usec. This error is expected to be negligible.

5.6 Summary

By placing the phase measuring device (the HP 5370 counter) in a wideband receiving system, the predictable errors of significance appear to be limited to bias and scale factor errors. For signal-to-noise ratios of 20 dB or higher in the wideband receiver IF, the phase noise due to the receiving system will be 4° or less. The magnitude of the transmitter and beacon induced phase noise is not known and must be measured.

6.0 RECOMMENDED AUGMENTED CSP CONFIGURATION FOR INITIAL TESTING AND ANALYSIS

6.1 Test Philosophy

In order to determine the accuracy with which IG coefficients can be obtained from ambiguous range data, estimations could be made with suitable software such as "TRAM" which is now being developed by the Performance Analysis Department. (Reference 9). The information contained in previous sections could be used to develop an error model for the ambiguous range data to be used in TRAM. However, it is highly probable that significant measurement errors may exist which have not yet been identified. Such errors, if any, could be identified in a program of field testing.

6.2 Preliminary Phase Noise Evaluation

Preliminary tests should be conducted to determine the magnitude of the transmitter and beacon induced phase noise in a wideband receiver. This could be accomplished by monitoring the radar's 30 MHz IF output on the SAMTEC beacon test set.

Phase measurements would be made at several signal strength levels, and a plot made of phase noise versus signal-to-noise ratio.

6.3 GEOS-III Satellite Tracking Tests

The GEOS-III satellite has a CSP beacon that is compatible with the WTR radar systems. Furthermore, the GEOS-III ephemerides are independently calculated by the Navy Weapons Surface Laboratory. These data are routinely compared with radar measurements for analysis and calibration purposes.

It is therefore recommended that one CSP radar system be augmented to measure ambiguous range, and that the results be compared to GEOS-III ephemeris data in order to estimate accurate, noise, and systematic errors. The recommended radar configuration is presented in Section 6.4. Data processing considerations are presented in Section 7.

It would also be instructive to schedule the WSMR DVES system (see 4.2) to track the satellite or passes which provide simultaneous visibility from SAMTEC and WSMR sites. Data collected by the DVES system could then be used to evaluate the SAMTEC CSP system and vice versa.

6.4 Test Configuration

The configuration suggested in this section is recommended for an initial period of testing as most of the equipment is either in the SAMTEC inventory or can be leased. Furthermore, very little "black box" development is required. Rather, the test configuration can be quickly set up using off-the-shelf commercial equipment. Only the "counter arm" circuitry requires development, and the circuitry for this unit is extremely simple. It could be readily developed by the SAMTEC West or purchased from one of several local vendors.

Referring to Figure 7, the shaded boxes represent equipment which can be borrowed from the SAMTEC inventory. The boxes with dotted edges represent new equipment which could be leased or purchased. The remaining equipment is available in the SAMTEC inventory and could presumably be borrowed for test periods between missile launches. All equipment could be placed in a SAMTEC test van, thus minimizing setup problems at the radar site. The following interfaces to the radar system could be made in approximately one hour or less:

- One C-band RF splitter and cable installed at the radar's parametric amplifier output. (This requirement favors the MPS-36 radar as the parametric amplifier output is available on a flatbed trailer which is easily accessible.)
- One BNC cable run from the radar's cesium standard output to the test van.
- One BNC cable run from the radar's time code generator 1 pps output to the test van.
- 60 cycle power, 10 amp outlet.

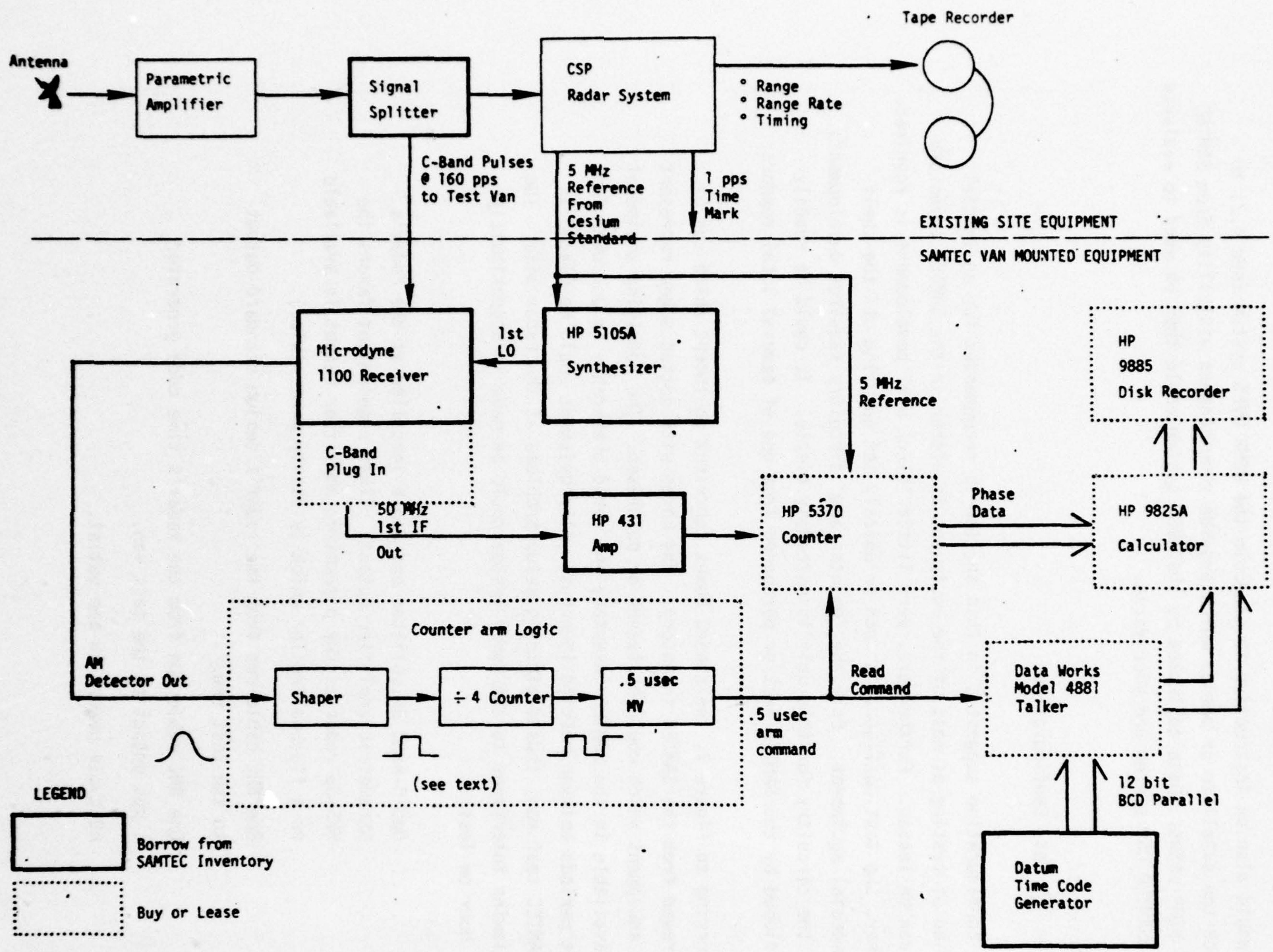

FIGURE 7 RECOMMENDED CONFIGURATION FOR AUGMENTED CSP SYSTEM FIELD TESTING

Prior to a satellite pass, the 1 pps on-time pulse from the radar will be compared to the 1 pps on-time pulse from the test van timing generator. The van's timing generator will be adjusted to obtain coincidence to within ±5 usec. including cable delay.

In operation, the radar will track satellites of opportunity. Range, azimuth, elevation range rate and timing data will be recorded on a standard magnetic tape.

In the augmented test van, the average phase of every fourth pulse[10] received and timing will be recorded on the disc. (see Figure 7) The radar data (magnetic tape) and van data (disc) will be processed as described in Section 7 to obtain ambiguous range data.

The technique used to synchronize the phase measurement of the return pulses requires mention as special circuitry is required. Each output pulse from the receiver is shaped and used to trigger a counter. The output of this counter is a 40 Hz square wave. Positive transitions trigger a monostable multivibrator with a fast rise time (.05 usec. max.) and a .5 usec. period. The 5370 counter is armed for this .5 usec. interval. Waveshapes and timing relationships are shown in Figure 8. Note in this figure that the normal circuit delays are used to ensure that the counter is armed (and the phase measurement made) during the portion of the pulse when the signal-to-noise ratio is nearly maximum.

The leading edge of the arming pulse is also used to command the time code generator to read into the 4881 buffer (talker). Consequently, timing data is provided with the same precision as the time code generator output, ± .1 usec.

---

[10] The standard HP 5370 counter cannot output processed data at 160 sps. The manufacturer indicates that modified units could output raw data at this rate. For initial testing, however, it is not considered practical to order special units. Consequently, the sampling rate is reduced to 40 sps.

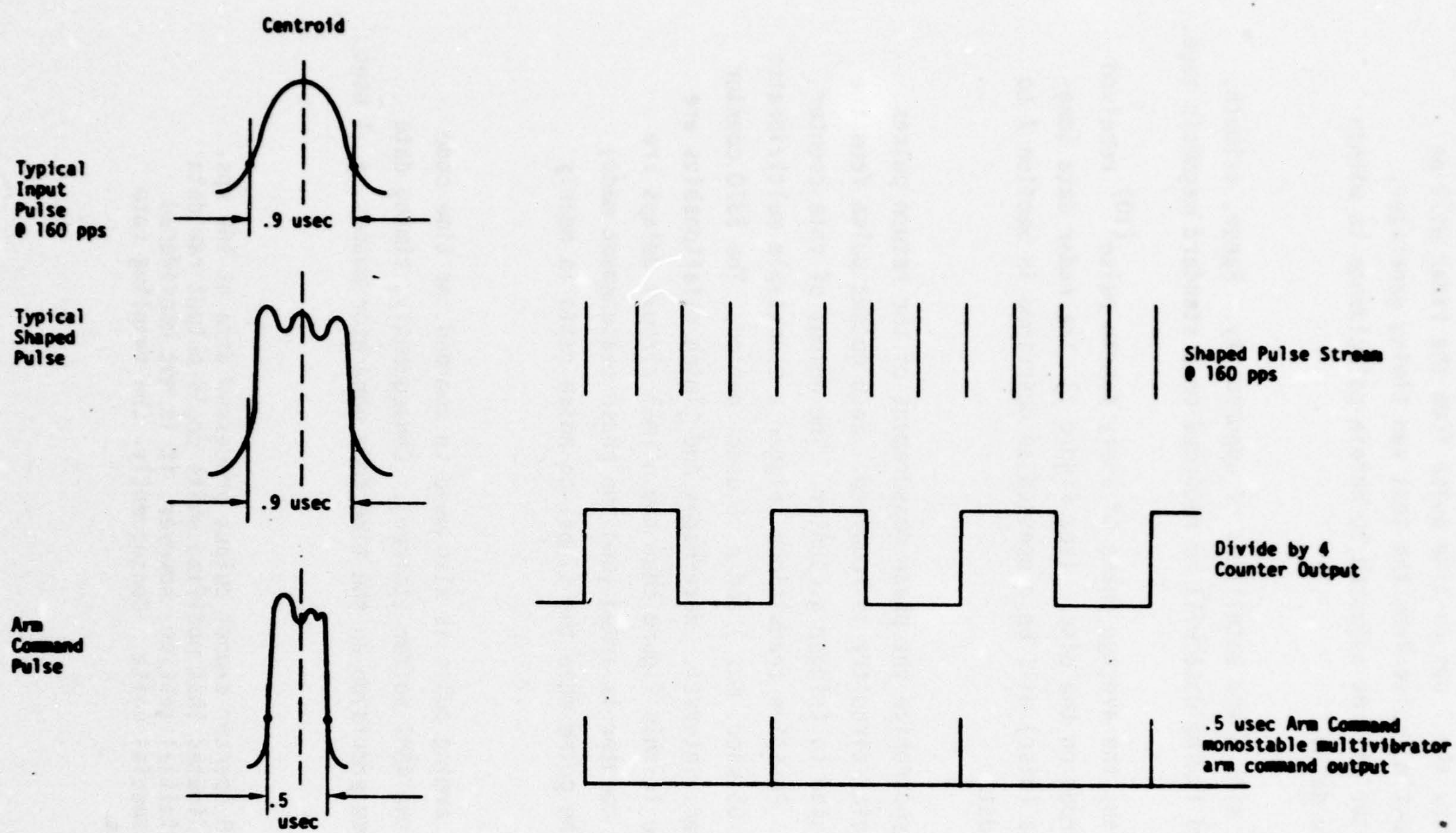

FIGURE 8 PULSE SHAPES AND TIMING RELATIONSHIPS IN THE AUGMENTED CSP SYSTEM

7.0 DATA PROCESSING CONSIDERATIONS

As described in Section 6, the ambiguous range data gathered by the augmented CSP radar will consist of the following:

a. Radar range, azimuth, elevation, range rate and timing data at a 10 sps rate recorded on magnetic tape in the standard SAMTEC format.

b. Ambiguous phase data and timing at a 40 sps rate recorded on a magnetic disc. (The sampling rate can be raised to 160 sps with a modified counter.)

These data will be processed as described in subsequent paragraphs in order to obtain information which can be utilized to develop system error models.

7.1 Ambiguous Range Data Merging

In order to merge the data on disc with the data on tape, the disc unit will be transported to the telemetry receiving station at Oak Mountain, VAFB. The disc can be directly interfaced with the telemetry validation system at this facility to produce a standard 9 track digital tape. This tape and the radar data tape will then be loaded into the SAMTEC Sigma 7 computer in separate files. The Performance Analysis Department RPM software will be utilized to correct the radar data for all known errors. A subroutine will be developed to apply a first order acceleration correction to the range rate data so that the instantaneous range rate can be estimated at any specified time.[11] [12]

The corrected radar data and the ambiguous phase data can then be merged as follows:

a. At some time, T_1, when the elevation angle exceeds 5° and fineline phaselock is achieved, the nominal radar range will be utilized as an initialization point.

---

[11] Refer to Appendix 3 for a description of the acceleration correction requirements

[12] A description of the Performance Analysis Department RPM software is included in Reference 10.

b. At some time, $T_1 + \Delta T$, an ambiguous phase sample will be available. The range rate data will be used to calculate the change in range from T_1 to $T_1 + \Delta T$. This change in range will be added to the range obtained at T_1 to give the range to the vehicle at time $T_1 + \Delta T$. (This initial range value will contain a bias error.)

c. The range rate data, corrected for acceleration, will be used to determine the number of cycles of phase change between the pulse received at $T_1 + \Delta T$ and the next succeeding pulse. The number of cycles will be accurate to at least $\pm.5$ cycle. The average phase change between these same two pulses will then be provided from the ambiguous phase data. This is accomplished by differencing the pulse-to-pulse phase measurements. This procedure is then repeated for each succeeding pulse.

d. The number of cycles of phase change between successive pulses is entered in the two-way Doppler equation to obtain the change in range between pulses. The range changes are sequentially added to obtain a file of range versus pulse reception time. The RPM refraction correction will be utilized in this calculation.

e. The timing data used in the range data file has a precision of $\pm.1$ usec., a scale factor error less than $\pm 1 \times 10^{-11}$, and a bias with respect to UTC of less than ± 5 usec. Consequently, the data file can be converted from pulse reception time to UTC time.

Subroutines will be added to the Sigma 7 RPM software to accomplish the data merging described above.

7.2 Comparison of Ambiguous Range Data with Satellite Data

The present Sigma 7 RPM software converts satellite data to radar coordinates and provides plots of residual errors. These residuals will be analyzed to determine bias, noise content, trends and systematic errors. Error models of the ambiguous range system can then be generated.

8.0 MAJOR MILESTONES

The major milestones suggested for the ambiguous range field measurement program are shown in Figure 9.

Start Date-CSP Beacon Available

1. Determine Beacon Jitter on SAMTEC Beacon Test Set
2. Buy/Lease special test equipment required (See Figure 7) for field tests if Beacon Jitter is determined to be 36° or less, 1σ at a 20 dB IF signal-to-noise ratio.
3. Mount special test equipment on SAMTEC Van or in portable rack.
4. Conduct Satellite Tracking Tets on Targets of Opportunity.
5. Program sub-routine changes to SAMTEC RPM Software.
6. Compare field test data with Satellite Position data in SAMTEC RPM Software.
7. Develop System Measurement Error Models for input to TRAM Software.

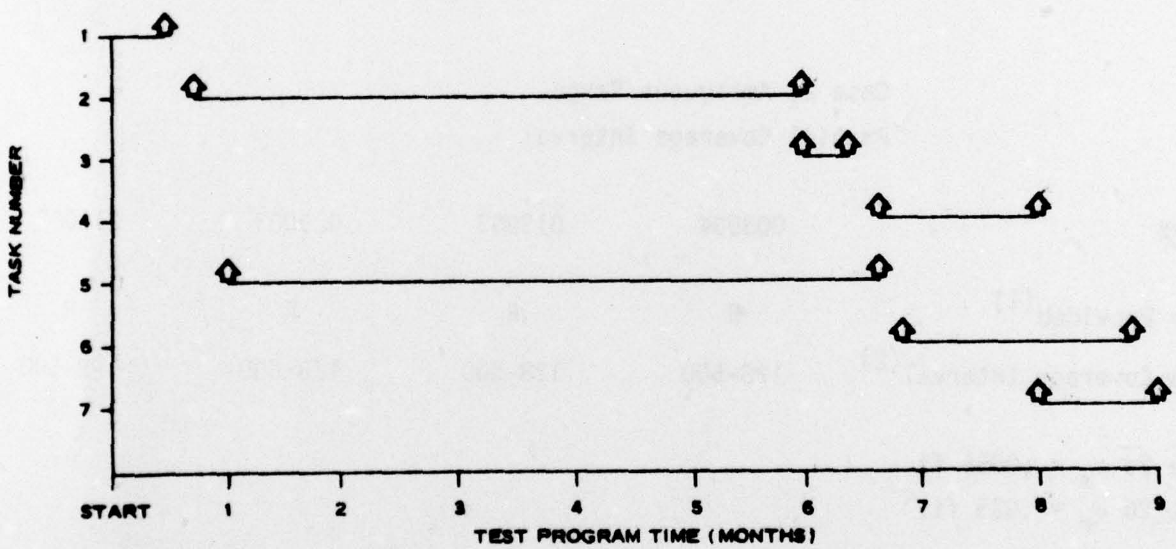

Figure 9 Field Test Program Key Milestones

TABLE 1

Case Descriptions of the Co-Variance Runs

Case 1, Ambiguous Range,
Full Coverage Interval

Sites	003004	013003	023003	213002
Data Provided[(1)]	R	R	R	R
Data Coverage Interval[(2)]	35-500	40-500	70-500	51-500

Case 1a σ_r = .0025 ft. (@ 10 pps .01 ft. @ 160 pps)
Case 1b σ_r = .025 ft. .1 ft.

Case 2, Ambiguous Range,
Partial Coverage Interval

Sites	003004	013003	023003	213002
Data Provided[(1)]	R	R	R	R
Data Coverage Interval[(2)]	128-500	128-500	128-500	128-500

Case 2a σ_r = .0025 ft.
Case 2b σ_r = .025 ft.

TABLE 1 (continued)

Case 3, Multistation RA$\dot{E}$R

Site	(003004) Point Mugu	(013003) SNI	(023003) VAFB	(213002) Pillar Point	(023002) VAFB	(213001) Pillar Point
Data Provided[1]	RAE$\dot{R}$	RAE$\dot{R}$	RAE$\dot{R}$	RAE$\dot{R}$	RAE	RAE
Data Coverage Interval[2]	35-500	40-500	70-500	51-500	16-500	125-500

Typical Measurement Uncertainties Used in Case 3:

$\sigma_r = 5(1 + 3 \times 10^{-7}R)$ ft.

$\sigma_a = \sigma_e = 10^{-4}(1 + 3 \times 10^{-7}R)$ radians

$\sigma_{\dot{r}} = 0.1$ ft./sec.

where

σ_r = uncertainty in range

R = range from the radar site to the vehicle, feet

σ_a = uncertainty in azimuth angle, rad.

σ_e = uncertainty in elevation angle, rad.

$\sigma_{\dot{r}}$ = uncertainty in range rate, ft./sec.

(1) RAE$\dot{R}$ indicates range, azimuth, elevation, range rate data.

(2) Intervals are plus seconds in the Minuteman flight.

TABLE 2

Recovery Ratio Results

Parameter	Case				
	1a	1b	2a	2b	3
1	.0065	.0590	.1101	.2828	.7250
2	.0040	.0323	.0081	.0573	.3143
3	.0152	.1230	.0603	.2203	.5075
4	.0303	.2877	.2178	.5994	.9887
6	.0110	.0907	.0332	.1064	.7896
8	.0087	.0856	.2307	.6412	.9041
16	.0568	.4594	.1062	.6102	.8873
19	.0382	.3098	.0728	.4135	.7132
21	.0087	.0713	.0185	.1178	.5534
26	.0927	.6400	.4203	.8677	.9437
28	.0470	.3322	.2356	.4881	.8127
30	.0091	.0832	.0522	.1927	.4799
43	.0005	.0042	.0016	.0115	.2369
44	.0013	.0120	.0070	.0620	.4892
52	.0009	.0082	.0013	.0104	.3029
53	.0073	.0656	.0223	.1263	.5308
61	.0008	.0067	.0014	.0108	.2637
62	.0075	.0669	.0223	.1289	.5514

TABLE 3

Parameter Number	Parameter Names
1	Platform Misalignment about X-axis
2	Platform Misalignment about Y-axis
3	Platform Misalignment about Z-axis
4	Independent drift rate of 2^{nd} gyro about 1^{st} control axis
6	g-dependent drift rate of 2^{nd} gyro about 1^{st} control axis, 1^{st} term
8	g^2-dependent drift rate of 2^{nd} gyro about 1^{st} control axis, 1^{st} term
16	independent rate of 1^{st} gyro about 2^{nd} control axis
19	g-dependent rate of 1^{st} gyro about 2^{nd} control axis, 2^{nd} term
21	g^2-dependent rate of 1^{st} gyro about 2^{nd} control axis, 2^{nd} term
26	independent rate of 1^{st} gyro about 1^{st} control axis
28	g-dependent rate of 1^{st} gyro about 1^{st} control axis, 1^{st} term
30	g^2-dependent rate of 1^{st} gyro about 1^{st} control axis, 1^{st} term
43	Accelerometer bias, 1^{st} piga
44	Scale Factor, 1^{st} piga
52	Accelerometer bias, 2^{nd} piga
53	Scale Factor, 2^{nd} piga
61	Accelerometer bias, 3^{rd} piga
62	Scale Factor, 3^{rd} piga

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3. Obtaining Doppler Data from an Unstable Transmitter, PA100-76-55, October 29, 1976.

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8. Refraction Study for SAMTEC Postflight Data Reduction, SAMTEC Task A7112.

9. SAMTEC XR Task Studies A6134, A6147, in progress.

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APPENDIX 1

Paragraph 3.4 Error in Range Measurement of the Telemetry Doppler System due to Phase Noise on the RF Carrier

For a RF transmitter frequency of 2.25×10^9 Hz.,

$$\frac{N}{\Delta T_i} = 2.25 \times 10^9 \frac{1}{1 + \frac{1}{C} \frac{\Delta R_i}{\Delta T_i}}$$

All terms were introducted in paragraph 4.4. Therefore,

$$\Delta R_i = C\Delta T_i \left(2.25 \times 10^9 \frac{\Delta T_i}{N} -1\right)$$

and

$$\frac{\Delta T_i}{N} \simeq \frac{\Delta T_r}{N}, \frac{\Delta T_i}{N} \simeq \frac{1}{2.25 \times 10^9}$$

$$\varepsilon_r \simeq - C \varepsilon_n \cdot \frac{\Delta T_i}{N} \quad \text{if } \varepsilon_n << N$$

where

ε_r = the error in ΔR_i

ε_n = the error in N due to phase jitter

Therefore,

$$\varepsilon_r \simeq \frac{- 1 \times 10^9 \varepsilon_n}{2.25 \times 10^9} \text{ or } .44 \varepsilon_n \text{ or } .002 \text{ ft.}$$

Paragraph 4.4 and Footnote 3

For N independent samples, the noise improvement, as compared to a single sample is theoretically equal to $\sqrt{N}$. Thus to equate data taken at 33 samples per second to data taken at 10 samples per second, the improvement is $\sqrt{\frac{33}{10}}$; at 100 sps $\sqrt{\frac{100}{10}}$, at 160 sps $\sqrt{\frac{160}{10}}$ etc.

Paragraph 4.1 Ambiguous Range Resolution for a .001 Hz Doppler Count

Each cycle of two-way Doppler at C-band represents a change in range of approximately .1 ft. By resolving the Doppler cycle count to .001 Hz, the system precision would be approximately .0001 ft. It is expected, however, that the transmitter and beacon phase jitter will exceed this value.

Paragraph 4.4 Error in Range Measurement of the Telemetry Doppler System due to a Timing Error.

As described in paragraph 4.4,

$$\Delta R_i = C\,\Delta T_i\,\frac{\Delta T_i - \Delta T_t}{\Delta T_t}$$

Therefore,

$$\varepsilon_r = \frac{\varepsilon_t\,C}{\Delta T_t}\left(2\Delta T_i - \Delta T_t\right)$$

where

ε_r is the error in ΔR_i

ε_t is the error in ΔT_i

the remaining terms were introduced in paragraph 4.4

$$\text{for } \Delta T_i \approx \Delta T_t,\ \varepsilon_r \approx \varepsilon_t C = (1 \times 10^{-11})\,(1 \times 10^{9}) = .01 \text{ ft.}$$

The speed of light is known to an accuracy of approximately 10 ft./sec. The transmitted frequency can be set to an accuracy of 1 part in 10^{11} on an operation-by-operation basis.

Consequently, at C-band,

$$\varepsilon_r \simeq (1 \times 10^{-9}) \, \Delta N$$

$$\Delta N \simeq 10 \text{ cycles per foot.}$$

Therefore,

$$\varepsilon_r \simeq 1 \times 10^{-8} \text{ ft. per ft. of range.}$$

APPENDIX 2

Telemetry Doppler Measurement Synchronization

When the HP 5370 Counter is armed by an external pulse, the measurement interval begins on the first positive going zero crossing of the data input and ends on the first positive going zero crossing after the arm pulse is removed. The counter can provide the following data: a) The number of integer zero crossings of the data input in the measurement. b) The integer number of clock zero crossings in the measurement interval. c) The partial fraction of the clock cycle which occurred between the first data positive going zero crossing and the first positive going clock zero crossing. d) The partial fraction of the clock cycle which occurred between the last positive going clock zero crossing and the last positive going data zero crossing.

In order to assure that the Counter 1 measurement ends on the same data zero crossing that the Counter 2 measurement begins, and vice versa, it is necessary to ensure that the arm pulse does not begin or end near a positive going data zero crossing. This is accomplished by combining the frame sync pulse with the data, and triggering the arm pulse start/stop on the negative going zero crossing of the data which first occurs after each frame sync pulse.

Use of this technique assures that the counters have approximately one-half of a data cycle to respond to the arm pulse transition before a positive going data zero crossing occurs.

It will be noted that the last partial cycle count on one counter plus the first partial cycle count on the succeeding counter must be one complete clock cycle. Thus, the precision of succeeding samples can be determined by checking how close to 1 cycle the two fractions are when summed. In the event that data samples are to be integrated, the actual sum would be rounded off to 1 cycle.

APPENDIX 3

Resolution of Doppler Count Ambiguities

In order to use ambiguous range data described in Section 6 of the basic report, the number of cycles of phase change between pulses must be resolved to less than $\pm.5$ cycles. For example, if the ambiguous phase measurement for one pulse is .57 cycle, and there are then 625.12 cycles of phase change to the next pulse, then the ambiguous measurement for the next pulse would be .69, and independent information would be required to indicate that the accrued phase shift was between 624.62 and 625.72 cycles. Thus, by differencing the two ambiguous phase measurements (.69 - .57) to obtain the fractional phase change of .12 cycles, and comparing this result to the independent information, it can be determined that the total phase change was 625.12 cycles.

In the event that there is noise in the ambiguous range data, however, the independent information accuracy requirement becomes more severe. For example, if the phase noise is .1 cy., 1σ, then the pulse-to-pulse difference uncertainty is approximately .14 cycles. For this noise level, the independent information provided should have an uncertainty of less than .36 cy., 1σ. This criteria can be met by computing the average velocity in each 1/160 sec. measurement interval to an accuracy of .036 (160) or 5.76 ft./sec. CSP data with a first order acceleration correction should readily meet this requirement.